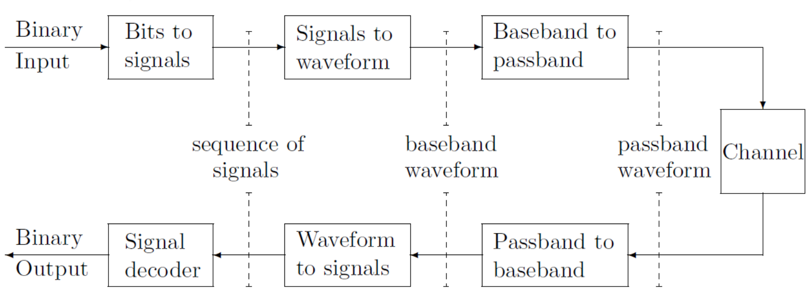
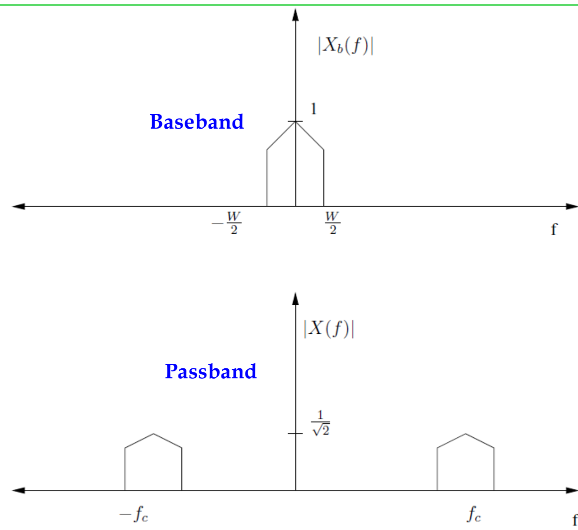
Lec08: Baseband Pulse Transmission

Baseband vs. Passband



❖ Reasons for modulation:

- ❑ Simultaneous transmission of several signals
- ❑ Practical Design of Antennas
- ❑ Exchange of power and bandwidth



Magnitude spectrum of the real baseband signal and its passband signal

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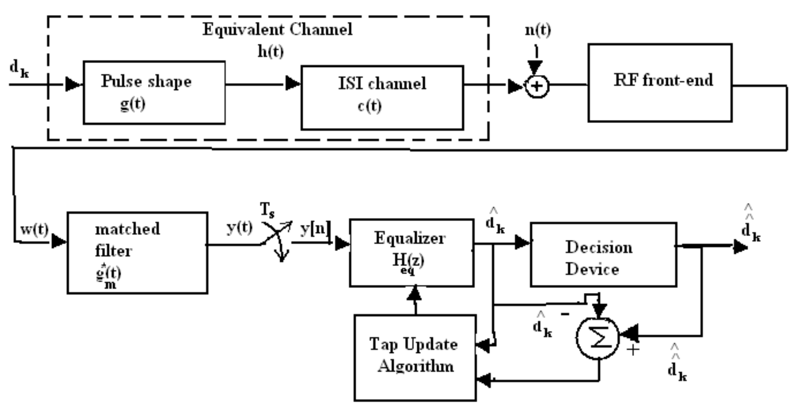
ISI-Free Transmission System



Fig(1)-Block Diagram of ISI-Free Transmission System

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Components of ISI-free transmission system

- Pulse shape g(t), used to improve the spectral properties of the transmitted signal.
- Matched filter, which is matched to the pulse shape g(t), used to maximize SNR of the received signal.
- Sampler, to sample the signal with higher rate than symbol-rate, and equalizer designed for the over-sampled signal (fractionally-spaced-equalization).
- Decision device, used to round the estimated symbol (o/p of the equalizer) to the training sequence.
- Tap-update algorithm, to update the tap coefficients to improve the performance of equalizer filter.

Introduction

- Transmission of *digital data (bit stream) over a noisy* baseband channel typically suffers two channel imperfections
  - Intersymbol interference (ISI)
  - Background noise (e.g., AWGN)
- These two interferences/noises often occur simultaneously.
- However, for simplicity, they are often separately considered in analysis.

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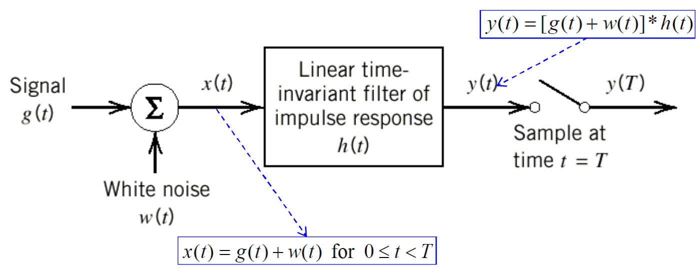
Matched filter

- Matched filter is a device for the optimal detection of a digital pulse.
  - It is named so because the *impulse response* of the matched filter matches the *pulse shape*.
- System model without ISI



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Design criterion

- To find *h(t)* such that the output signal-to-noise ratio SNR_O is maximized.

$$x(t) = g(t) + w(t) \text{ for } 0 \le t < T$$

$$\begin{aligned} y(t) &= [g(t)+w(t)] * h(t) \\ &= g(t) * h(t) + w(t) * h(t) \\ &= g_o(t) + n(t) \end{aligned}$$

$$SNR_O = \frac{|g_o(T)|^2}{E[n^2(T)]} \qquad \frac{\text{instantaneous power}}{\text{average power}}$$

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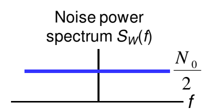
Analysis of matched filter

$$g_o(t) = \int_{-\infty}^{\infty} H(f)G(f)\exp(j2\pi ft)df$$

$$\Rightarrow |g_o(T)|^2 = \left|\int_{-\infty}^{\infty} H(f)G(f)\exp(j2\pi fT)df\right|^2$$

With $w(t)$ being white with PSD $N_0/2$,



$$S_N(f) = S_W(f)|H(f)|^2 = \frac{N_0}{2}|H(f)|^2$$

$$\Rightarrow E[n^2(T)] = \int_{-\infty}^{\infty} S_N(f)df = \frac{N_0}{2}\int_{-\infty}^{\infty}|H(f)|^2\, df$$

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Analysis of matched filter

$$\Rightarrow \eta = \frac{\left|\int_{-\infty}^{\infty} G(f)H(f)\exp(j2\pi fT)df\right|^2}{\frac{N_0}{2}\int_{-\infty}^{\infty}|H(f)|^2\, df}$$

Cauchy-Schwarz inequality

$$\left|\int_{-\infty}^{\infty} \phi_1(x)\phi_2(x)dx\right|^2 \le \left(\int_{-\infty}^{\infty}|\phi_1(x)|^2\, dx\right)\left(\int_{-\infty}^{\infty}|\phi_2(x)|^2\, dx\right)$$

with equality holds if, and only if, $\phi_1(x) = k\cdot\phi_2^*(x)$ for some constant k.

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❖By Cauchy-Schwarz's inequality,

$$\left|\int_{-\infty}^{\infty} H(f)G(f)\exp(j2\pi fT)df\right|^2 \le \int_{-\infty}^{\infty} |H(f)|^2\, df \cdot \int_{-\infty}^{\infty} |G(f)\exp(j2\pi fT)|^2\, df$$

$$\Rightarrow \eta \le \frac{\int_{-\infty}^{\infty} |H(f)|^2\, df \cdot \int_{-\infty}^{\infty} |G(f)|^2\, df}{\frac{N_0}{2}\int_{-\infty}^{\infty} |H(f)|^2\, df} = \frac{2}{N_0}\int_{-\infty}^{\infty} |G(f)|^2\, df$$

❖This is a constant bound, independent of the choice of *h(t)*.

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Hence, the optimal η is achieved by:

$$\boxed{H(f) = k \cdot G^*(f)\exp(-j2\pi fT)}$$

$$h_{\text{opt}}(t) = \int_{-\infty}^{\infty} k \cdot G^*(f)\exp(-j2\pi fT)\exp(j2\pi ft)df$$

$$= k\left(\int_{-\infty}^{\infty} G(f)\exp(j2\pi f(T-t)df\right)^*$$

$$= kg^*(T-t).$$

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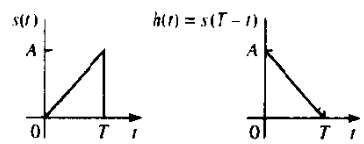
$$h_{opt}(t) = kg^{*}(T-t).$$

Hence, under additive white noise, the *optimal received filter* matches the input signal in the sense that it is a time-inversed and delayed version of the complex-conjugated input signal $g(t)$.

For real signal g(t) then $kg\ (T-t)$



(a) Signal $s(t)$

(b) Impulse response of filter matched to $s(t)$

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Properties of matched filter

- The maximum output signal-to-noise ratio only depends on the energy of the input, and is nothing to do with the pulse shape itself.
- Namely, whether the pulse shape is sinusoidal, rectangular, triangular, etc is irrelevant to the maximum output signal-to-noise ratio, as long as these pulse shapes have the same energy.

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The peak pulse signal-to-noise ratio of a matched filter depends only on the ratio of the signal energy to the power spectral density of the white noise at the filter input.

$$H_{opt}(f) = kG^*(f)\exp(-j2\pi fT)$$

$$\begin{aligned} G_o(f) &= H_{opt}(f)G(f) \\ &= kG^*(f)G(f)\exp(-j2\pi fT) \\ &= k|G(f)|^2\exp(-j2\pi fT) \end{aligned}$$

$$\begin{aligned} g_o(T) &= \int_{-\infty}^{\infty} G_o(f)\exp(j2\pi fT)\,df \\ &= k\int_{-\infty}^{\infty} |G(f)|^2\,df \end{aligned}$$

E

$$g_0(T) = kE$$

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$$\Rightarrow E[n^2(T)] = \int_{-\infty}^{\infty} S_N(f)df = \frac{N_0}{2}\int_{-\infty}^{\infty} |H(f)|^2\,df$$

$$H_{opt}(f) = kG^*(f)\exp(-j2\pi fT)$$

$$\sigma_n^2 = E[n^2(T)] = \frac{k^2 N_0}{2}\int_{\infty}^{-\infty} |G(f)|^2\,df$$

Variance

$$= \frac{k^2 N_0 E}{2}$$

$$\eta_{max} = \frac{(kE)^2}{(k^2 N_0 E/2)} = \frac{2E}{N_0}$$

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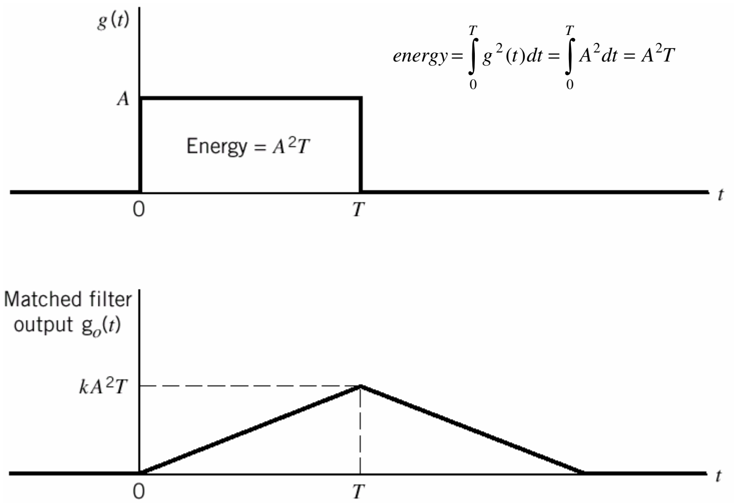
Example 4.1 Matched filter for rectangular pulse

$$energy = \int_0^T g^2(t)dt = \int_0^T A^2 dt = A^2 T$$



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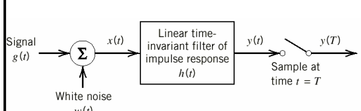

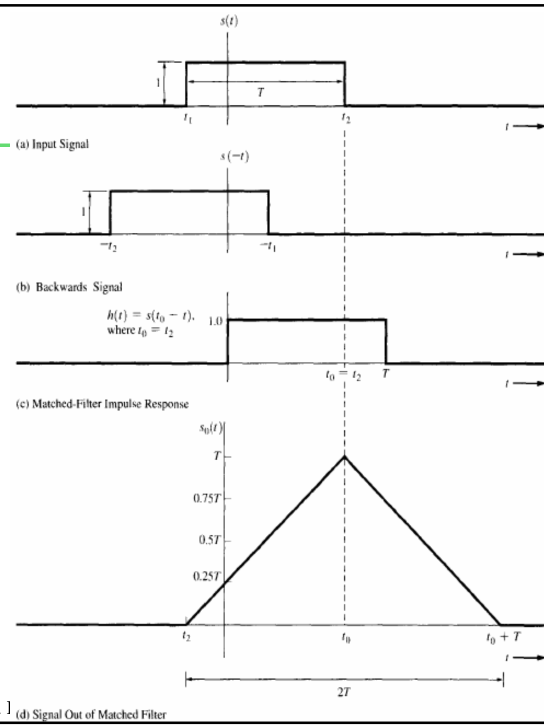

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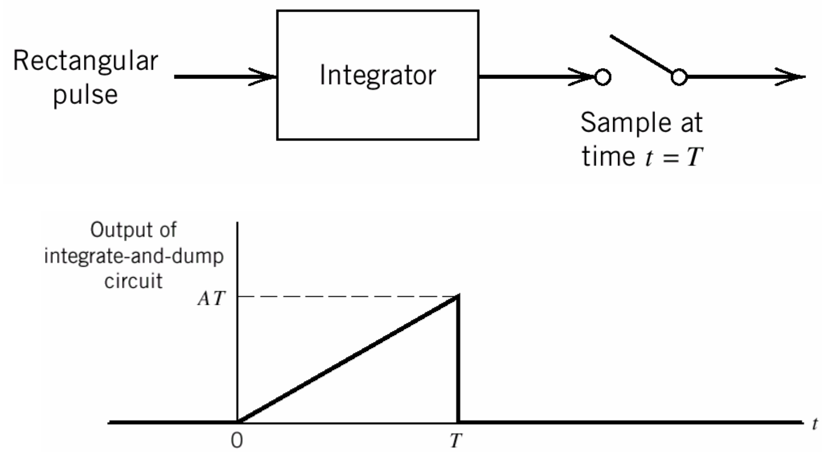
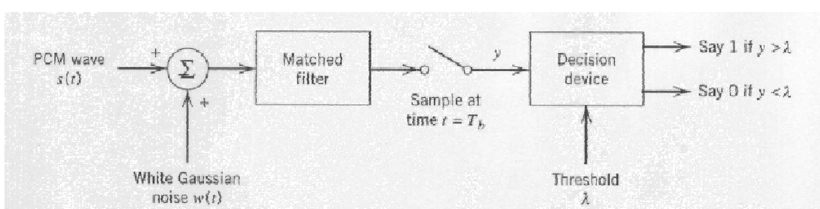
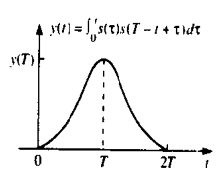


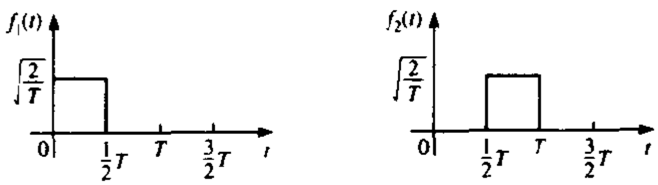


The matched filter output is the autocorrelation function of $s(t)$.



Example 5-1-2

Consider the $M = 4$ biorthogonal signals shown in Fig. 5-1-8 for transmitting information over an AWGN channel. The noise is assumed to have zero mean and power spectral density $\frac{1}{2}N_0$. Let us determine the basis functions for this signal set, the impulse responses of the matched-filter demodulators, and the output waveforms of the matched-filter demodulators when the transmitted signal is $s_1(t)$.



(a)

$$f_1(t) = \begin{cases} \sqrt{2/T} & (0 \le t \le \frac{1}{2}T) \\ 0 & \text{(otherwise)} \end{cases}$$

$$f_2(t) = \begin{cases} \sqrt{2/T} & (\frac{1}{2}T \le t \le T) \\ 0 & \text{(otherwise)} \end{cases}$$

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$$f_1(t) = \begin{cases} \sqrt{2/T} & (0 \le t \le \frac{1}{2}T) \\ 0 & \text{(otherwise)} \end{cases}$$

$$f_2(t) = \begin{cases} \sqrt{2/T} & (\frac{1}{2}T \le t \le T) \\ 0 & \text{(otherwise)} \end{cases}$$

$$h_1(t) = f_1(T-t) = \begin{cases} \sqrt{2/T} & (\frac{1}{2}T \le t \le T) \\ 0 & \text{(otherwise)} \end{cases}$$

$$h_2(t) = f_2(T-t) = \begin{cases} \sqrt{2/T} & (0 \le t \le \frac{1}{2}T) \\ 0 & \text{(otherwise)} \end{cases}$$

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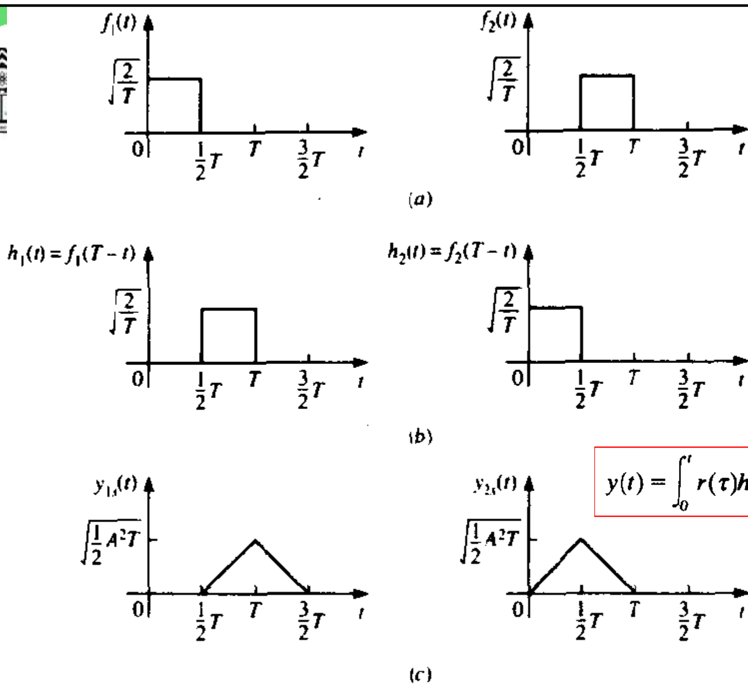


$$y(t) = \int_0^t r(\tau)h(t-\tau)\,d\tau$$

Basis functions and matched filter responses for Example 5-1-2.

filter outputs at the sampling instant $t = T$ is

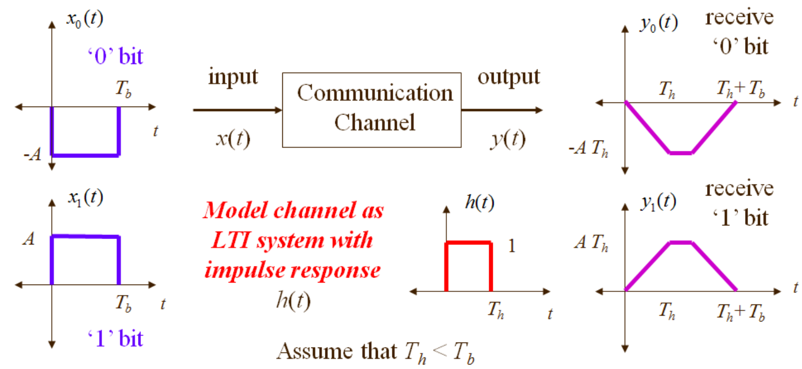
$$\mathbf{r} = [r_1 \quad r_2] = [\sqrt{\mathscr{E}} + n_1 \quad n_2]$$

where $n_1 = y_{1n}(T)$ and $n_2 = y_{2n}(T)$ are the noise components at the outputs of the matched filters, given by

$$y_{kn}(T) = \int_0^T n(t) f_k(t)\,dt, \qquad k = 1, 2 \tag{5-1-35}$$

ISI

- **Analog transmission over communication channels**
- **Two-level digital PAM over channel that has memory but does not add noise**



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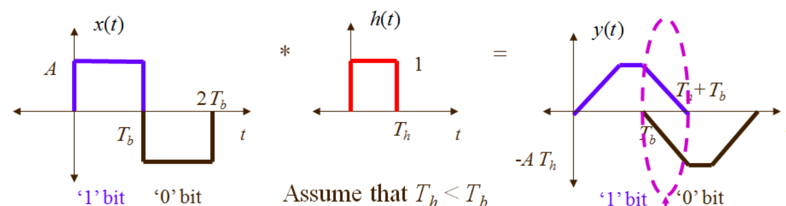
Transmit Two Bits (Interference)

- **Transmitting two bits (pulses) back-to-back will cause overlap (interference) at the receiver**



- **Sample $y(t)$ at T_b, $2\ T_b$, …, and threshold with threshold of zero**
- **How do we prevent intersymbol interference (ISI) at the receiver?**

Intersymbol interference

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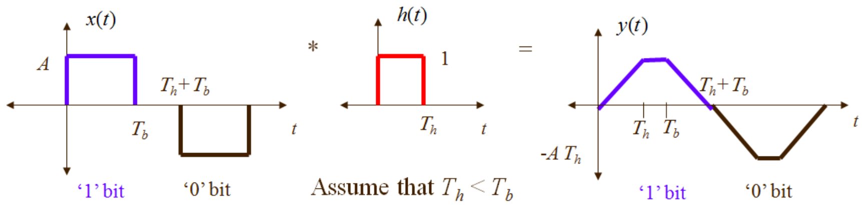
Transmit Two Bits (No Interference)

- **Prevent intersymbol interference by waiting T_h seconds between pulses (called a guard period)**



Nyquist's criterion for distortionless baseband binary transmission

- **Disadvantages?**

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Ideal Nyquist channel

- The simplest $P(f)$ that satisfies Nyquist criterion is the rectangular function:

$$P(f)=\begin{cases} T_b, & |f|<W=\dfrac{1}{2T_b} \\ 0, & |f|>W=\dfrac{1}{2T_b} \end{cases} \text{ and } P(-W)+P(W)=T_b.$$

$$\Rightarrow p(t)=\frac{\sin(2\pi Wt)}{2\pi Wt}=\mathrm{sinc}(2Wt)$$

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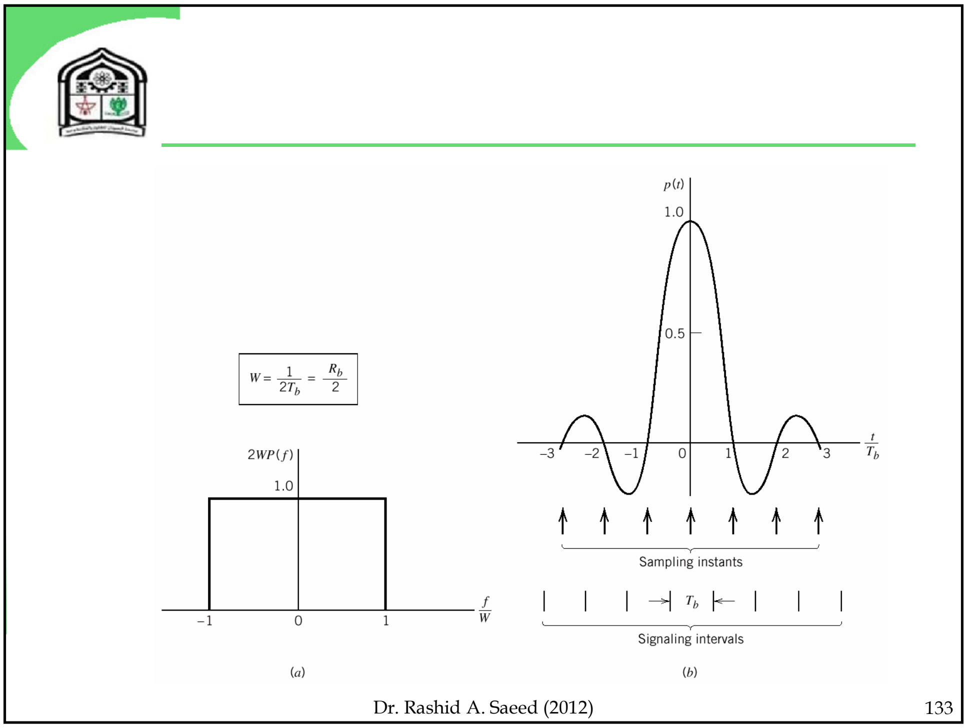
$W = \frac{1}{2T_b} = \frac{R_b}{2}$
2WP(f)
1.0
−1
0
1
f/W
(a)
p(t)
1.0
0.5
−3
−2
−1
0
1
2
3
t/T_b
Sampling instants
T_b
Signaling intervals
(b)
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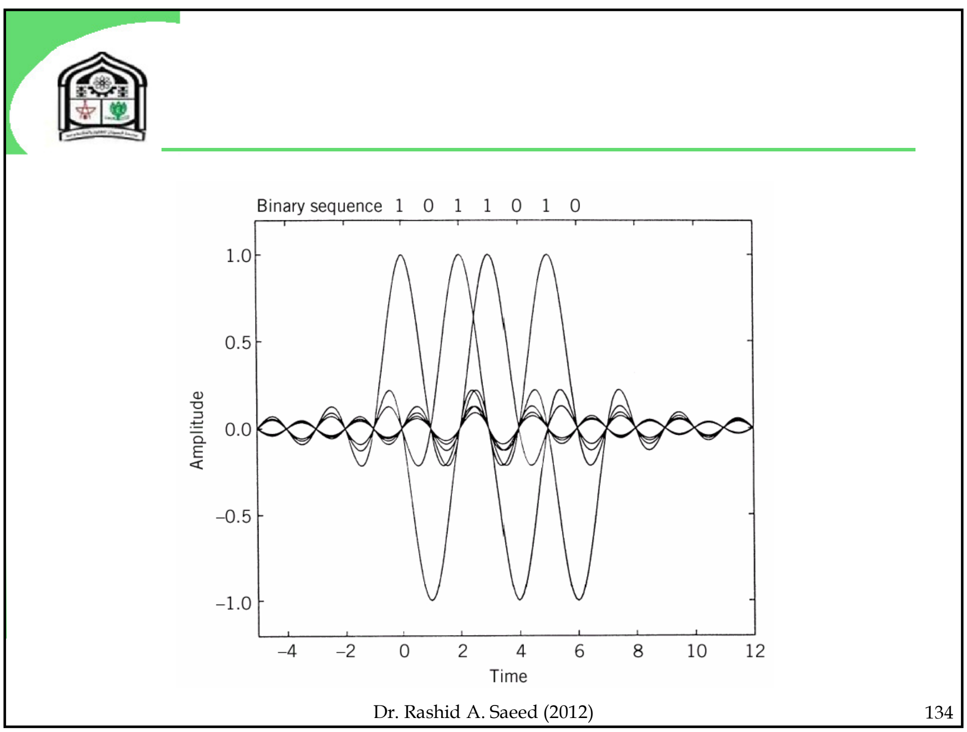
Binary sequence 1 0 1 1 0 1 0
1.0
0.5
0.0
−0.5
−1.0
Amplitude
−4
−2
0
2
4
6
8
10
12
Time
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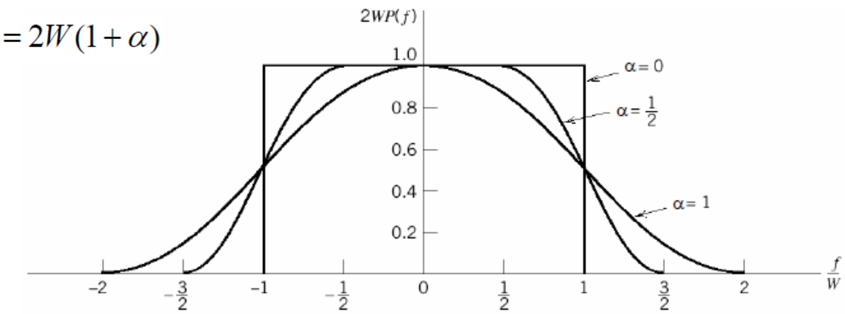
Raised Cosine Spectrum

$$B_T = 2W(1+\alpha)$$



where α is the rolloff factor, which is the *excess bandwidth* over the ideal solution.

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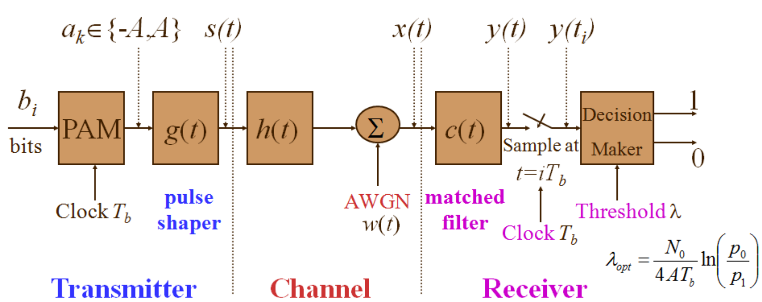
Digital 2-level PAM System



- **Transmitted signal** $s(t) = \sum_k a_k\, g(t - k\,T_b)$
- **Requires synchronization of clocks between transmitter and receiver**

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Exercise

Simon Haykin book

Problem (4.1) and Problem (4.2)

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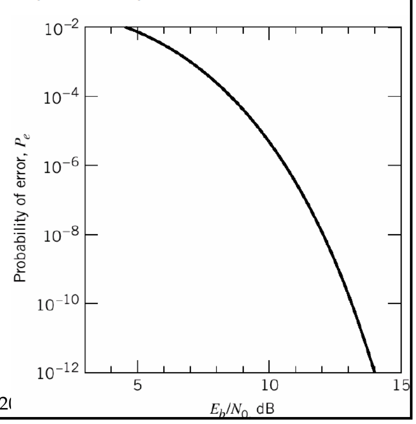
Error rate due to noise

$$BER_{opt} = \frac{1}{2}\operatorname{erfc}\left(\sqrt{\frac{E_g}{N_0}}\right) = Q\left(\sqrt{\frac{2E_g}{N_0}}\right)$$

The ratio of the transmitted energy per bit to the noise spectral density



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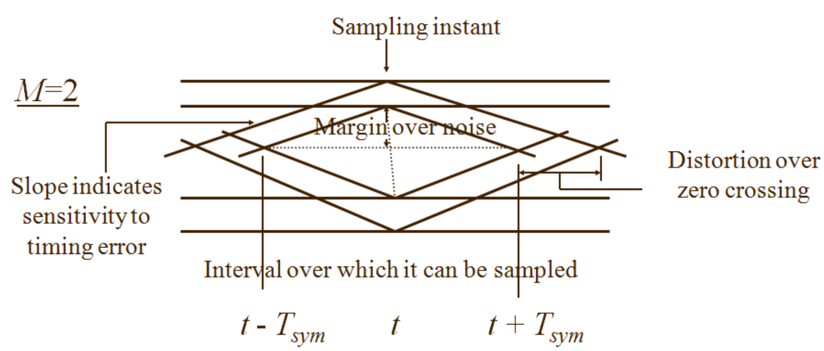
- **PAM receiver analysis and troubleshooting**



- **The more open the eye, the better the reception**

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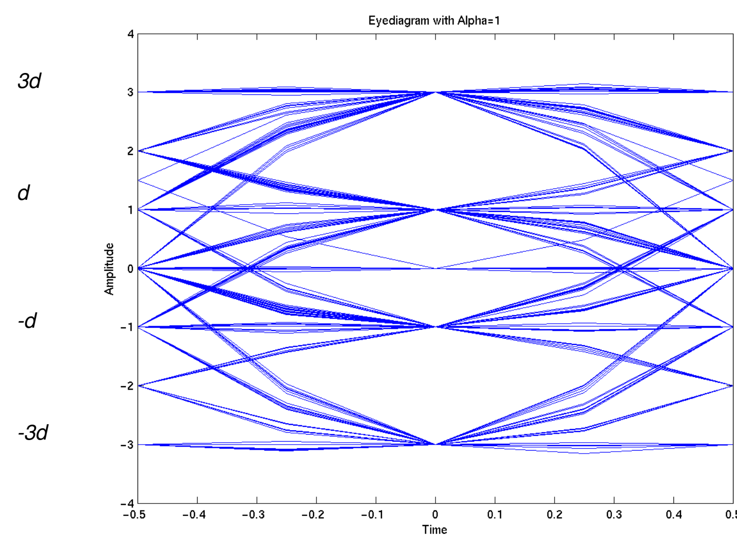
Eye Diagram for 4-PAM



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EQUALIZATION

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Introduction

- *Equalization*, *diversity*, and *channel coding* are three techniques which can be used independently or in tandem to improve received signal quality.
- Equalization at receiver compensates for *intersymbol interference (ISI)* created by multipath
- the term equalization can be used to describe any signal processing operation that minimizes ISI.

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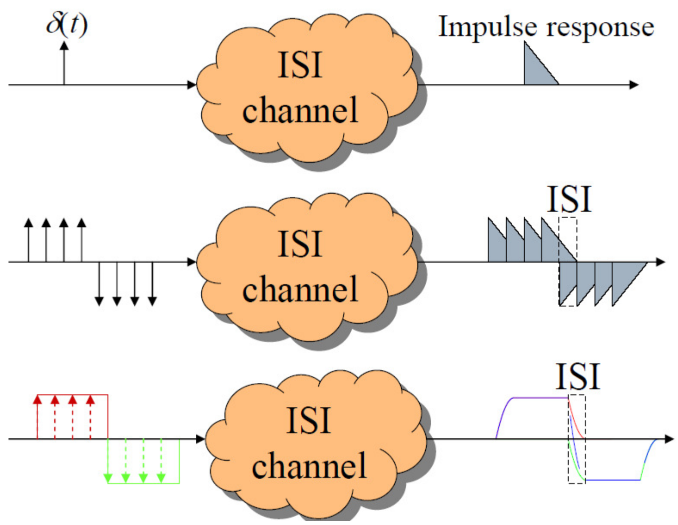
ISI



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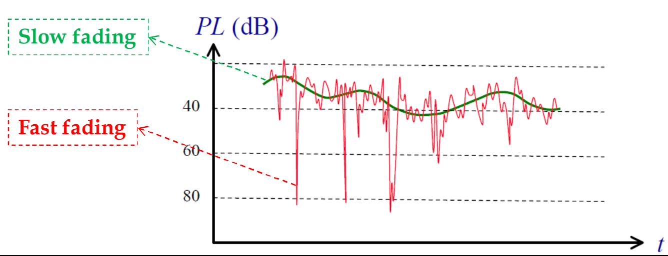
Countermeasures

	flat	frequency selective
slow	DIVERSITY CODING+INTERL.	EQUALIZATION
fast	DIVERSITY CODING+INTERL.	DIVERSITY CODING+INTERL.



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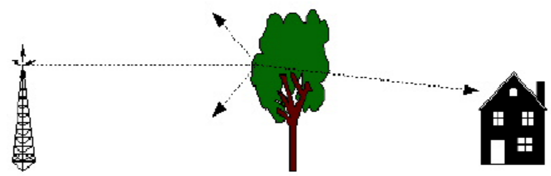
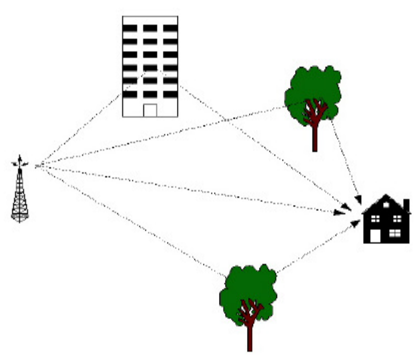
Flat Fading



Flat Fading is caused by absorbers between the two antennae and is countered by antenna placement and transmit power level.

Frequency Selective Fading



Frequency selective fading is caused by reflectors between the transmitter and receiver creating multi-path effects.

Equalization

$$s(t) \rightarrow \boxed{h_{ch}(t)} \rightarrow r(t)=h_{ch}(t)*s(t)$$

$$s(t) \rightarrow \boxed{h_{ch}(t)} \rightarrow r(t) \rightarrow \boxed{h_{eq}(t)} \rightarrow x(t)= h_{ch}(t)* h_{eq}(t)*s(t)$$

$$x(t)= s(t) \;\Rightarrow\; h_{ch}(t)* h_{eq}(t)=\delta(t)$$

$$H_{eq}(f)= 1/H_{ch}(f)$$

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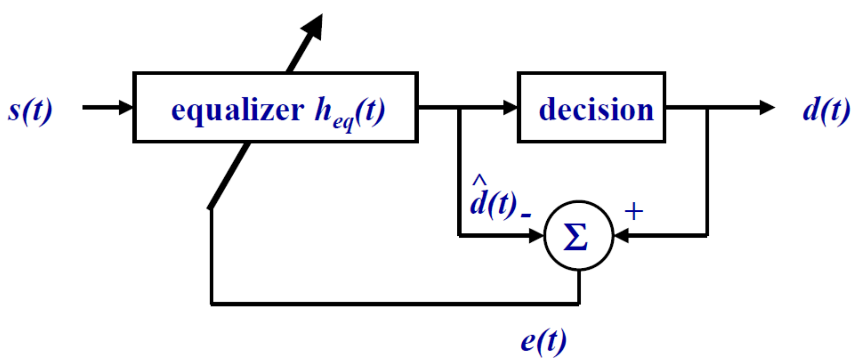
Adaptive equalization



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Need For Equalization

- **Need For Equalization:**
  - Overcome ISI degradation
- **Need For Adaptive Equalization:**
  - Changing Channel in Time
  - means: Training, and Tracking
- => Objective:

Find the Inverse of the Channel Response to reflect a ‘delta channel to the Rx

Types of Equalization techniques

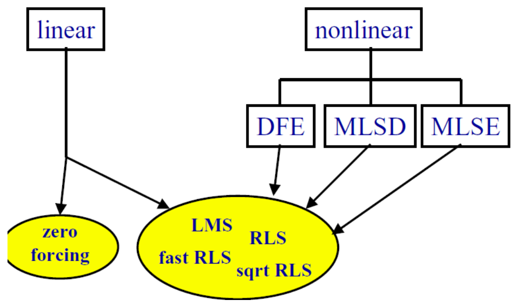
Linear Equalization techniques

which are simple to implement, but greatly enhance noise power because they work by inverting channel frequency response.

Non-Linear Equalization techniques

which are more complex to implement, but have much less noise enhancement than linear equalizers.

Equalizer classification



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Types of Equalizer

- ZFE: Zero Forcing Equalizer
- MSE: Mean Square Error
  - LS: Least Square
  - LMS: Least Mean Square
- MMSE: Minimum mean square error
- Blind Equalization
- Turbo Equalization
- Viterbi Equalizer

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Lec09: Passband Digital Transmission

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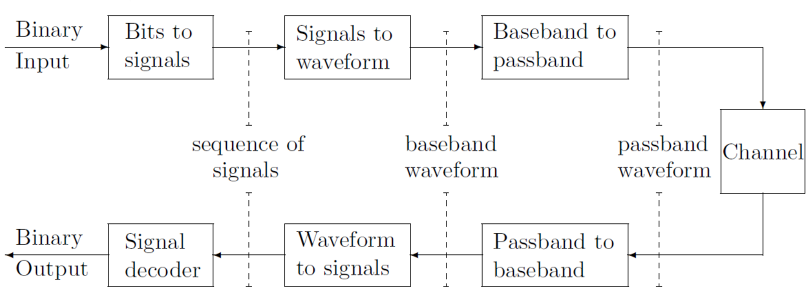
Baseband vs. Passband



- ❖ Reasons for modulation:
  - ❑ Simultaneous transmission of several signals
  - ❑ Practical Design of Antennas
  - ❑ Exchange of power and bandwidth

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Passband Digital Transmission

- Introduction – Categories of digital communications (ASK/PSK/FSK)
- Three basic signaling schemes in digital communications

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Digital Modulation techniques

- Digital modulation is the process by which a sequence of pulses (message) of duration T is transformed into a sequence of sinusoidal waveforms, s(t) of duration T.
- The general form of the modulated signal is:

$$s(t) = A(t).\cos[2.\pi.(f_c + f_m(t)).t + \theta(t)]$$

- Digital modulation can then be defined as the process whereby the amplitude, frequency, phase or a combination of them is varied in accordance with the information to be transmitted
- A scheme that uses:
  - amplitude is called ASK (Amplitude Shift Keying)
  - frequency is called FSK (Frequency Shift Keying)
  - phase is called PSK (Phase Shift Keying)

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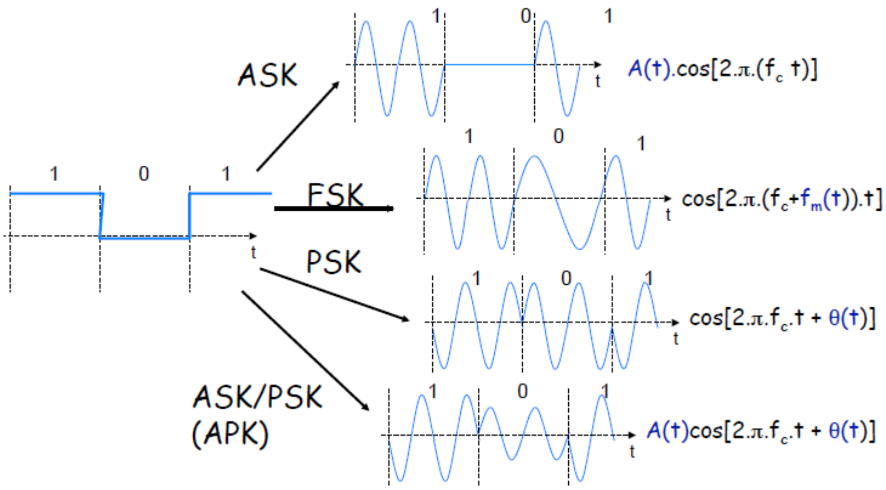
Digital Modulation techniques: Illustration



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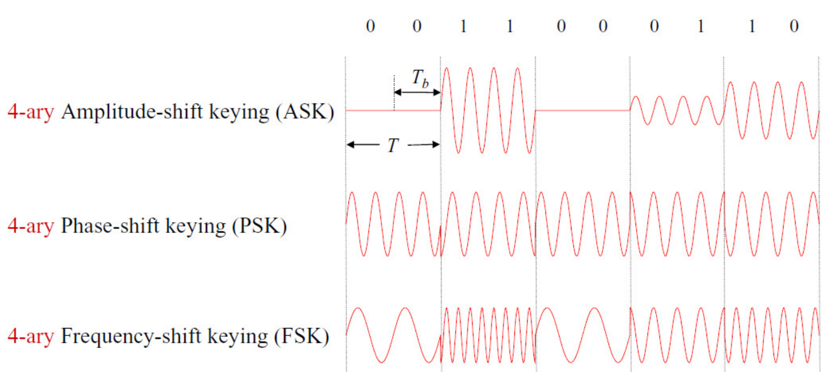
Categories of M-ary digital communications (ASK/PSK/FSK)

- Three basic signaling schemes in *M-ary digital* communications



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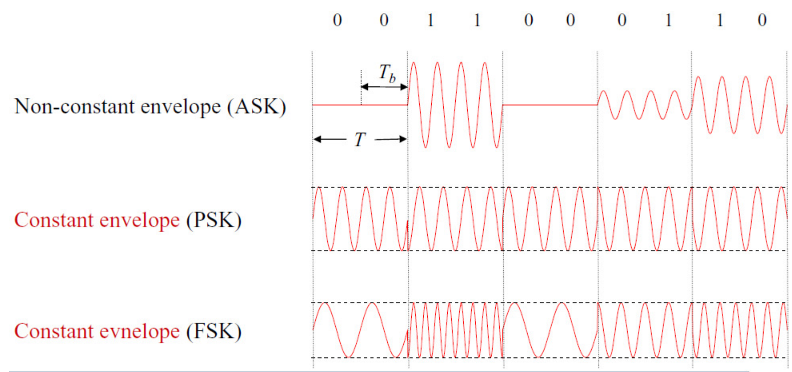
Constant Envelope versus Non-Constant Envelope

- ❖Constant envelope: A necessity for non-linear channels



Coherent versus Non-Coherent

- ❖Coherent technique
  - ❑The transmitter and receiver are required to be synchronized in both carrier phase and bit timing.
- ❖Non-Coherent technique
  - ❑The transmitter and receiver are **not** required to be synchronized in both carrier phase and bit timing.

MSK

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- Minimum shift keying (MSK)
- Goal: avoid sudden change.
- Two frequencies are used, $f_2 = 2f_1$.
- Separate into even and odd bits.
- The duration of each bit is doubled.
  - A higher frequency is chosen if even and odd bits are equal.
  - The signal is inverted if the odd bit equals 0.

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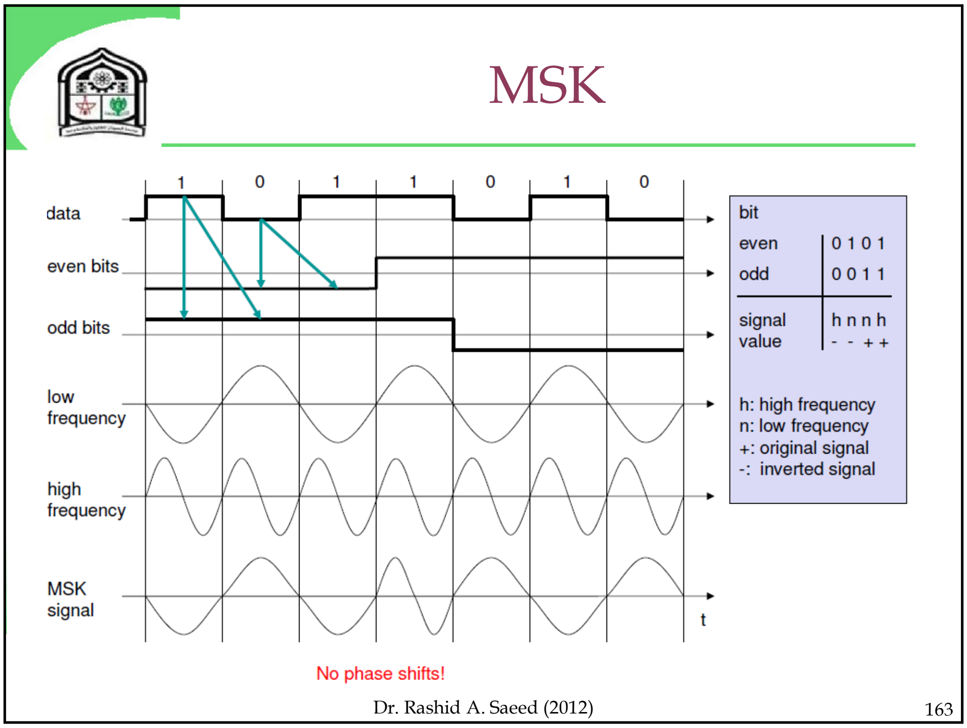
MSK
1 0 1 1 0 1 0
data
even bits
odd bits
low frequency
high frequency
MSK signal
t
bit
even 0 1 0 1
odd 0 0 1 1
signal value h n n h
- - + +
h: high frequency
n: low frequency
+: original signal
-: inverted signal
No phase shifts!
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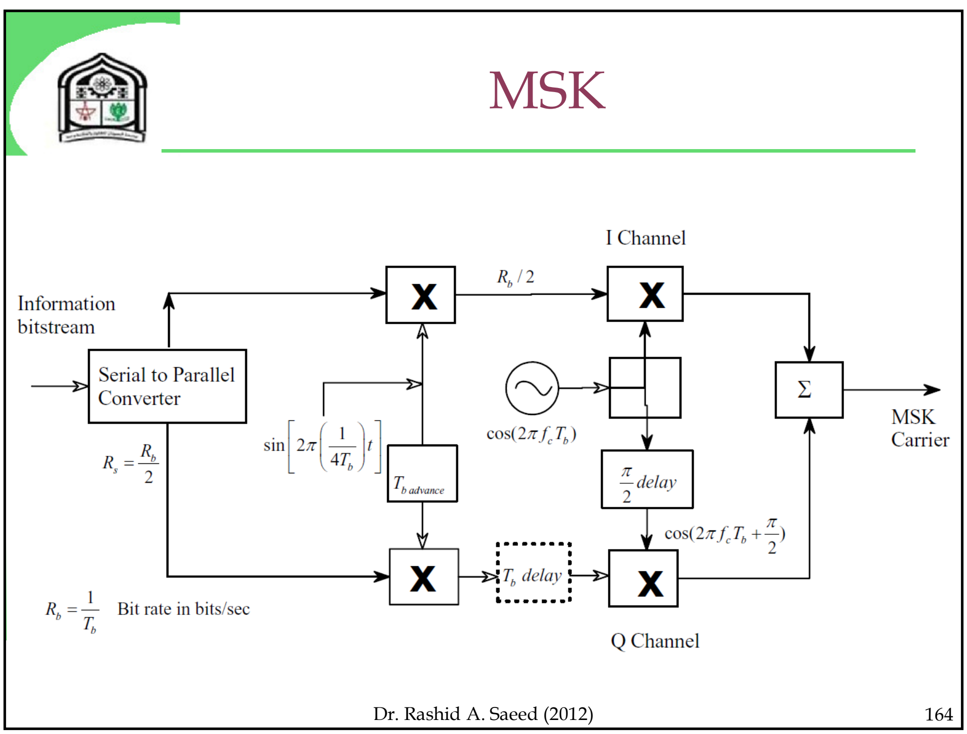
MSK
I Channel
Information bitstream
Serial to Parallel Converter
$R_s = \frac{R_b}{2}$
$R_b / 2$
$\sin\left[2\pi\left(\frac{1}{4T_b}\right)t\right]$
$T_{b\ advance}$
$\cos(2\pi f_c T_b)$
$\frac{\pi}{2}$ delay
$\cos(2\pi f_c T_b + \frac{\pi}{2})$
T_b delay
X
Σ
MSK Carrier
$R_b = \frac{1}{T_b}$ Bit rate in bits/sec
Q Channel
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GMSK

- Using Gaussian pulse shape instead of half sinusoidal signal

GMSK is used in several mobile systems around the world. Global Speciale Mobile (GSM), Digital European Cordless Telephone (DECT), Cellular Digital Packet Data (CDPD), DCS1800 (Digital Communications System in the 1800 MHz band) in Europe, and GSM-based PCS1900 (Personal Communications Services in the 1900 MHz band) in the U.S. uses GMSK.

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PSK

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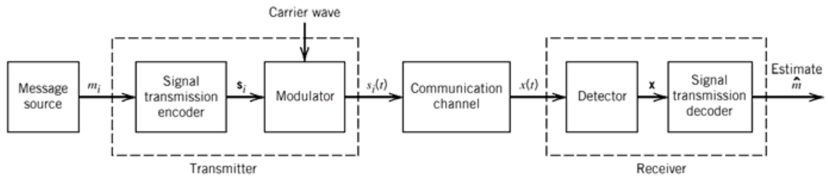
Coherent phase-shift keying



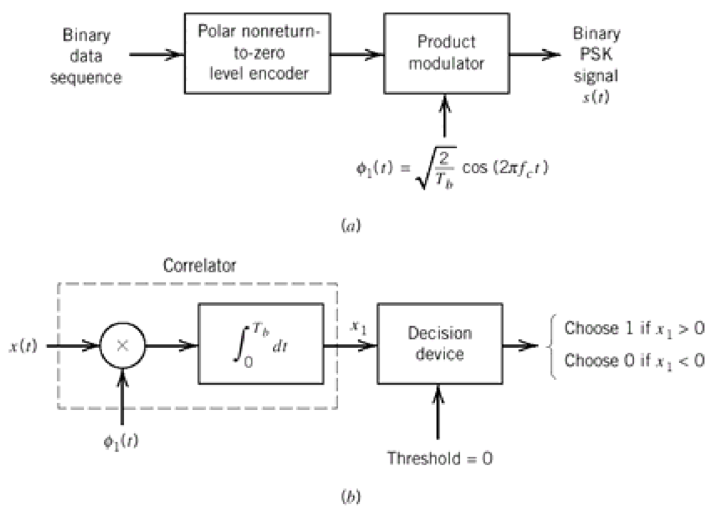
- Binary PSK

$$s_1(t) = \sqrt{\frac{2E_b}{T_b}}\cos(2\pi f_c t)$$

$$s_2(t) = \sqrt{\frac{2E_b}{T_b}}\cos(2\pi f_c t + \pi) = -\sqrt{\frac{2E_b}{T_b}}\cos(2\pi f_c t)$$

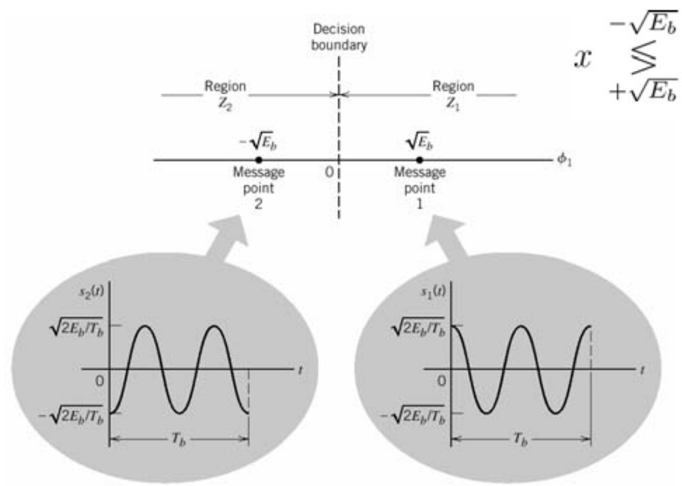
for $0 \le t < T_b$, where T_b is a multiple of $1/f_c$.

Coherent PSK



PSK: Signal-space diagram

$$x \underset{+\sqrt{E_b}}{\overset{-\sqrt{E_b}}{\lessgtr}} 0$$



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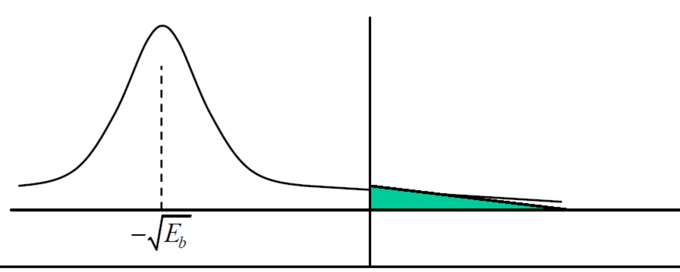
BER

- What is the probability that the signal point ***r*** falls in $\boldsymbol{Z_1}$ given $\mathbf{s_2}(t)$ was transmitted? (Conditional probability)
- ***r*** = $\mathbf{s_2}$ + ***n*** is a normally distributed random variable with mean $-\sqrt{E_b}$ and variance $N_0/2$.

$$P_e = \int_0^\infty \frac{1}{\sqrt{\frac{N_0}{2}}\sqrt{2\pi}} \exp - \left[\frac{\left(x+\sqrt{E_b}\right)^2}{N_0} \right] dx$$



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$$Let \quad Z = \frac{\left(x+\sqrt{E_b}\right)}{\sqrt{\frac{N_0}{2}}}, \quad dZ = \frac{dx}{\sqrt{\frac{N_0}{2}}}$$

$$When \;\; x = 0, \quad Z = \sqrt{\frac{2E_b}{N_0}}$$

$$P_e = \int_{\sqrt{\frac{2E_b}{N_0}}}^{\infty} \frac{1}{\sqrt{2\pi}} \exp\left(\frac{-Z^2}{2}\right) dz = Q\left(\sqrt{\frac{2E_b}{N_0}}\right)$$

$$= Q(\gamma_b)$$

$$P(\text{Error}) = \Phi\left(-\sqrt{2\frac{E_b}{N_0}}\right) \Rightarrow \Phi(-x) = \frac{1}{2}\text{erfc}\left(\frac{x}{\sqrt{2}}\right) \Rightarrow P_e = \frac{1}{2}\,\text{erfc}\left(\sqrt{\frac{E_b}{N_0}}\right)$$

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Coherent M-ary PSK

$$s_i(t) = \begin{cases} \sqrt{\frac{2E}{T}} \cos\left[2\pi f_c t + (2i-1)\frac{\pi}{4}\right], & 0 \le t < T \\ 0, & \text{elsewhere} \end{cases}$$

where $i = 1, 2, 3, 4$, f_c is a multiple of $1/T$,

E is the transmitted energy per symbol, and
T is the symbol duration.

TABLE 6.1 *Signal-space characterization of QPSK*

Gray-encoded Input Dibit	Phase of QPSK Signal (radians)	Coordinates of Message Points s_{i1}	s_{i2}
10	$\pi/4$	$+\sqrt{E/2}$	$-\sqrt{E/2}$
00	$3\pi/4$	$-\sqrt{E/2}$	$-\sqrt{E/2}$
01	$5\pi/4$	$-\sqrt{E/2}$	$+\sqrt{E/2}$
11	$7\pi/4$	$+\sqrt{E/2}$	$+\sqrt{E/2}$

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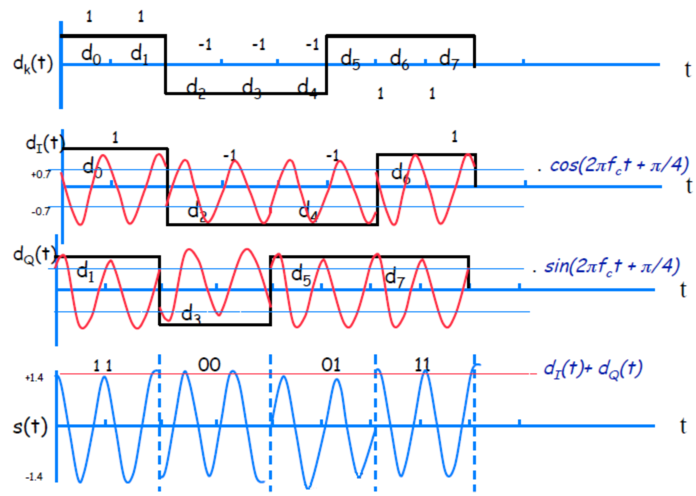
QPSK



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Vector space analysis of QPSK

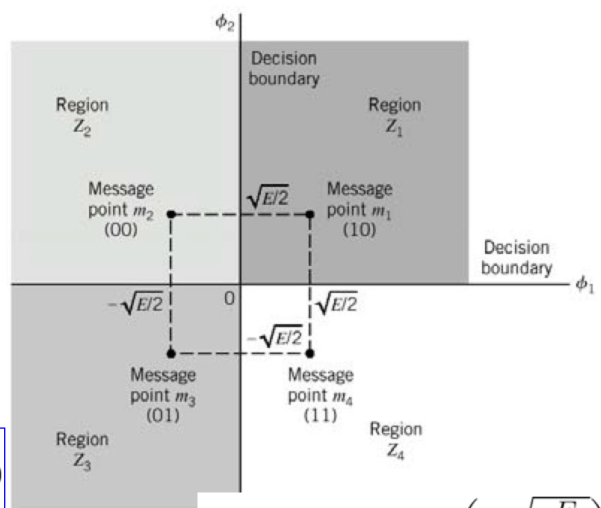
$$s_i = \begin{bmatrix} \sqrt{E}\cos\left((2i-1)\frac{\pi}{4}\right) \\ -\sqrt{E}\sin\left((2i-1)\frac{\pi}{4}\right) \end{bmatrix} \text{ with } \begin{cases} \phi_1(t) = \sqrt{\frac{2}{T}}\cos(2\pi f_c t) \\ \phi_2(t) = \sqrt{\frac{2}{T}}\sin(2\pi f_c t) \end{cases}$$

Two-dimensional signal space diagram of QPSK

$$P_e \simeq \operatorname{erfc}\left(\sqrt{\frac{E}{2N_0}}\right)$$

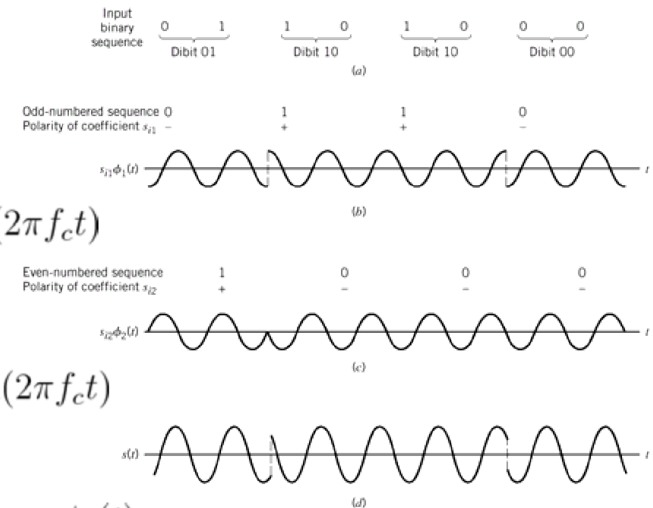
$$E = 2E_b,$$

$$x_1 \underset{+\sqrt{E/2}}{\overset{-\sqrt{E/2}}{\lessgtr}} 0 \text{ and } x_2 \underset{+\sqrt{E/2}}{\overset{-\sqrt{E/2}}{\lessgtr}} 0$$



$$\text{Bit Error Rate} = \Phi\left(-\sqrt{2\frac{E_b}{N_0}}\right)$$

$$\Rightarrow x_1 \underset{+\sqrt{E/2}}{\overset{-\sqrt{E/2}}{\lessgtr}} 0 \text{ and } x_2 \underset{+\sqrt{E/2}}{\overset{-\sqrt{E/2}}{\lessgtr}} 0$$



$$\phi_1(t) = \sqrt{\frac{2}{T}}\cos(2\pi f_c t)$$

$$\phi_2(t) = \sqrt{\frac{2}{T}}\sin(2\pi f_c t)$$

$$s(t) = s_{i1}\phi_1(t) + s_{i2}\phi_2(t)$$

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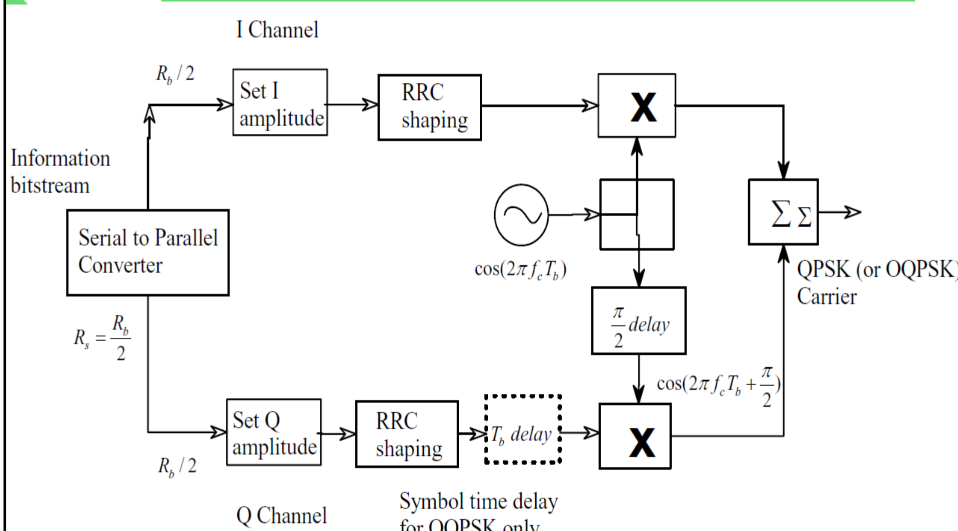
QPSK/OQPSK



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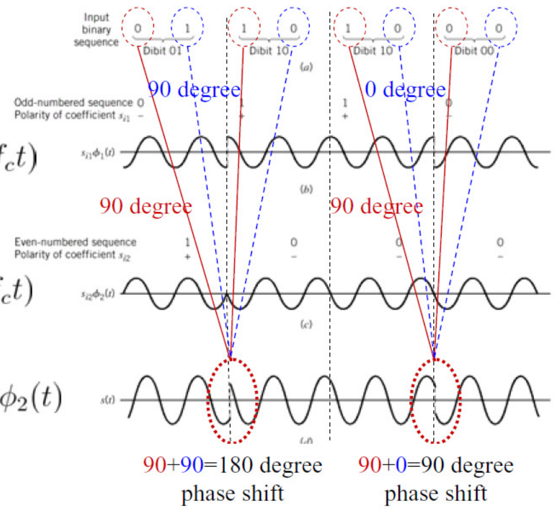
Coherent PSK– Offset QPSK

- Example 6.1:
  - QPSK

$$\phi_1(t) = \sqrt{\frac{2}{T}}\cos(2\pi f_c t)$$

$$\phi_2(t) = \sqrt{\frac{2}{T}}\sin(2\pi f_c t)$$

$$s(t) = s_{i1}\phi_1(t) + s_{i2}\phi_2(t)$$



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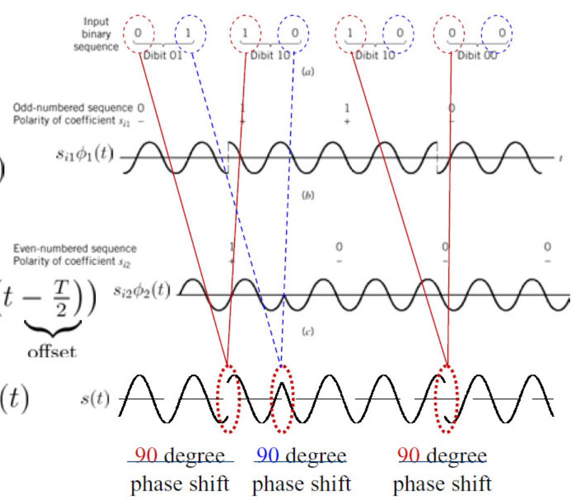
OQPSK

- Example 6.1:
  - Offset QPSK

$$\phi_1(t) = \sqrt{\frac{2}{T}}\cos(2\pi f_c t)$$

$$\phi_2(t) = \sqrt{\frac{2}{T}}\sin\left(2\pi f_c \underbrace{\left(t - \frac{T}{2}\right)}_{\text{offset}}\right)$$

$$s(t) = s_{i1}\phi_1(t) + s_{i2}\phi_2(t)$$



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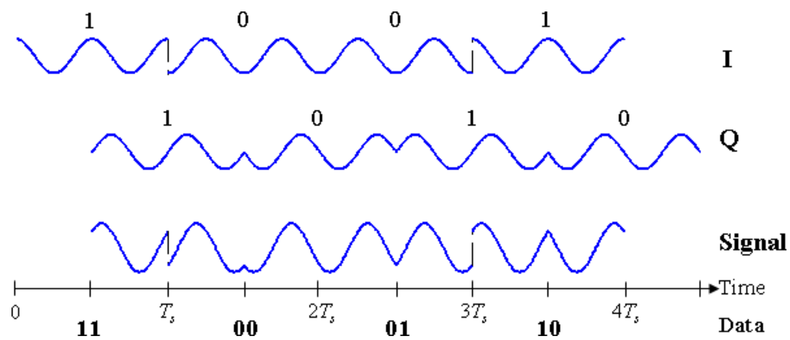
OQPSK



- In OQPSK, bit transition and therefore carrier modulation can occur more frequently (every T) but with a smaller phase shift (+/-90°).
  - The envelope never goes to zero

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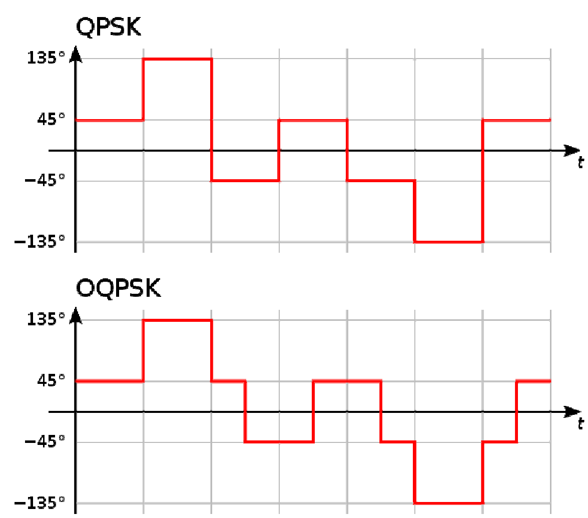
QPSK vs. OQPSK



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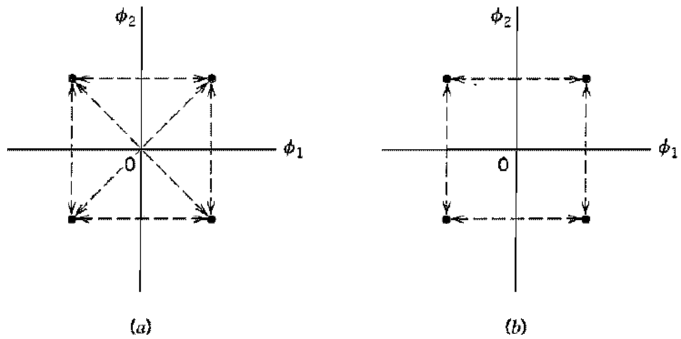

FIGURE 6.10 Possible paths for switching between the message points in (*a*) QPSK and (*b*) offset QPSK.

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π/4 - QPSK

- Has easy demodulation and has been adopted for use in, for example, TDMA cellular telephone systems.
- This also reduces the phase-shifts from a maximum of 180°,
  - but only to a maximum of 135° and
  - so the amplitude fluctuations of π/4–QPSK are between OQPSK and non-offset QPSK.

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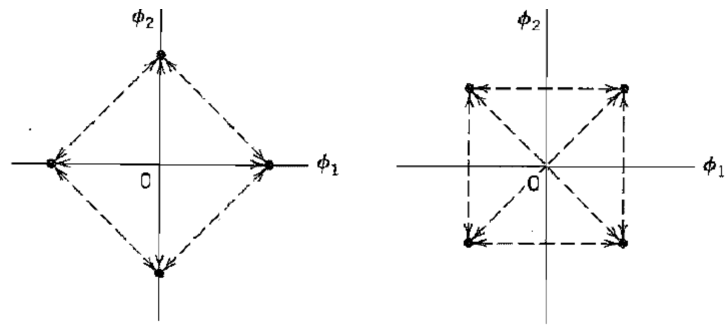
π/4 - QPSK



(a) (b)

- Unlike offset QPSK signals, $\pi/4$-shifted QPSK signals can be noncoherently detected, thereby considerably simplifying the receiver design. Moreover, like QPSK signals, $\pi/4$-shifted QPSK can be differently encoded, in which case we should really speak of *$\pi/4$-shifted DQPSK*.

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TABLE 6.2 *Correspondence between input dibit and phase change for π/4-shifted DQPSK*

Gray-Encoded Input Dibit	*Phase Change, Δθ (radians)*
00	$\pi/4$
01	$3\pi/4$
11	$-3\pi/4$
10	$-\pi/4$

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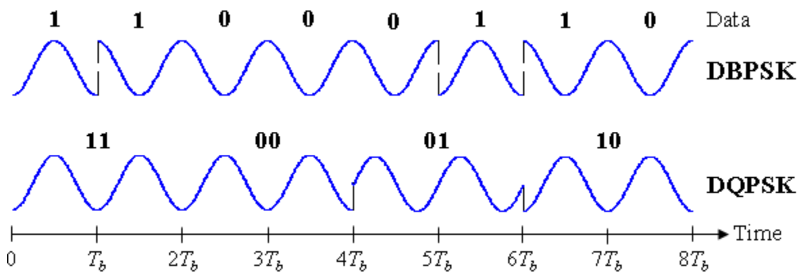
Differentially encoded QPSK (DQPSK)



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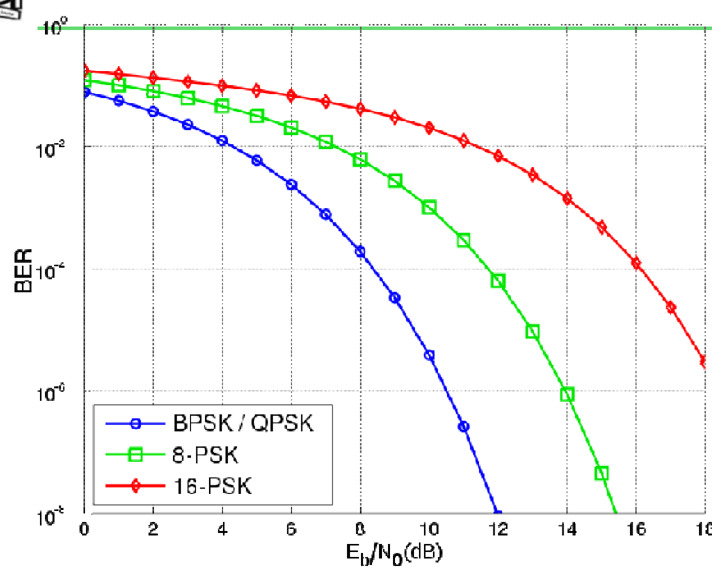
Energy vs. Spectrum efficiency



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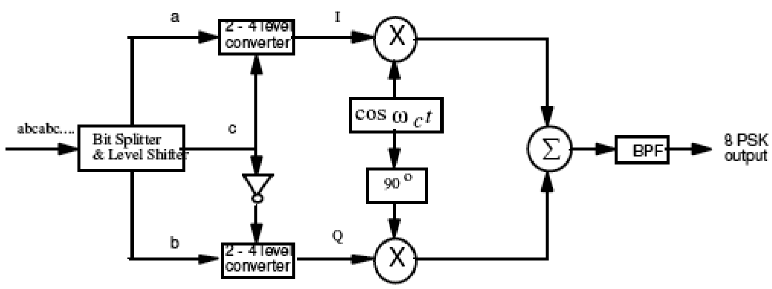
8PSK



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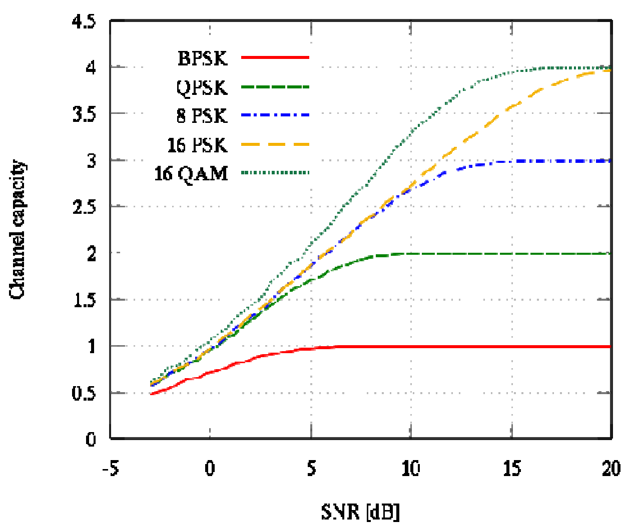
Capacity



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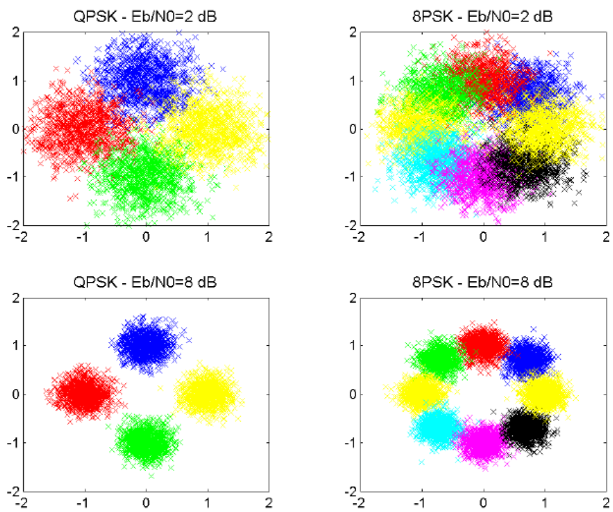
Example of samples of matched filter output for some bandpass modulation schemes



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QAM

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Amplitude and Phase modulation

- A variety of communication protocols implement QAM.
- Current protocols such as Wi-Fi and DVB, for example, both utilize 64-QAM modulation.
- In addition, emerging wireless technologies such as WiMAX, 802.11n, and HSDPA/HSUPA will implement QAM as well.
- Thus, understanding QAM is important because of its widespread use in current and emerging technologies.

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- With M-ary QAM, the amplitude and phase of the signal are both changed

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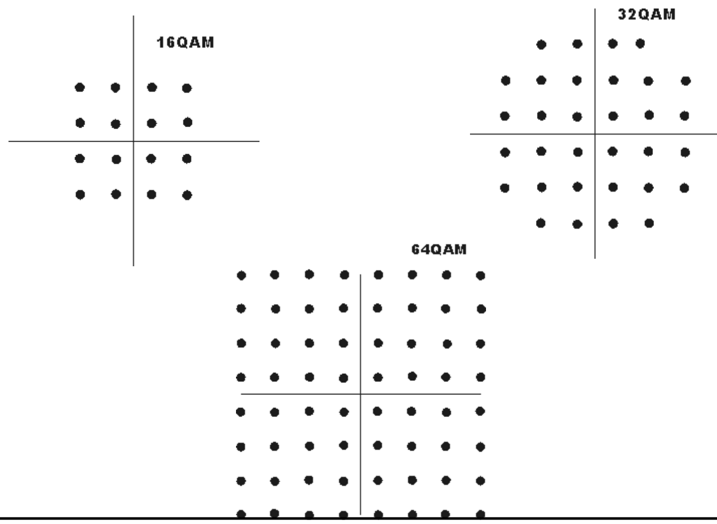
Constellation diagrams for QAM



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QAM bits per symbol

MODULATION	BITS PER SYMBOL	SYMBOL RATE
BPSK	1	1 x bit rate
QPSK	2	1/2 bit rate
8PSK	3	1/3 bit rate
16QAM	4	1/4 bit rate
32QAM	5	1/5 bit rate
64QAM	6	1/6 bit rate

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Applications

- GSM: GMSK
- CDMA
  - Forward channels: QPSK
  - Reverse Channels: OQPSK
- EDGE: 8PSK
- E-EDGE: 16-32QAM
- LTE: 64QAM

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Lec 10: Spread Spectrum

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Introduction

- Spread Spectrum first is developed for military applications
  - Where resistance to jamming (interference) was the major concern

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SS

- SS are:
  - Direct Sequence –SS
    - SS code + PSK
  - Frequency Hopping SS
    - Changing the carrier in a Pseudo random manner
- Both techniques rely on pseudo noise sequence to perform the SS.

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Pseudo Noise Sequence

- To generate PN sequence, use *feedback shift register.*

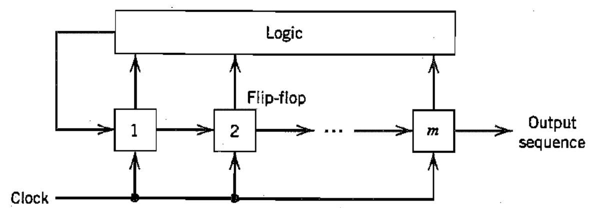


FIGURE 7.1 Feedback shift register.

EXAMPLE 7.1

100, 110, 111, 011, 101, 010, 001, 100, ...

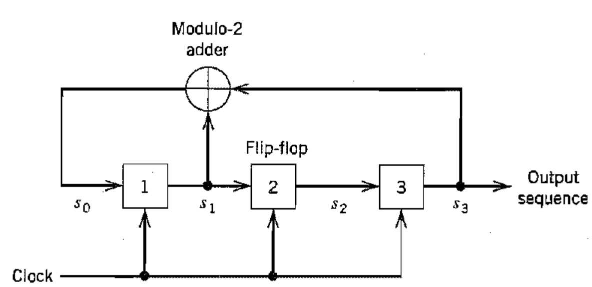
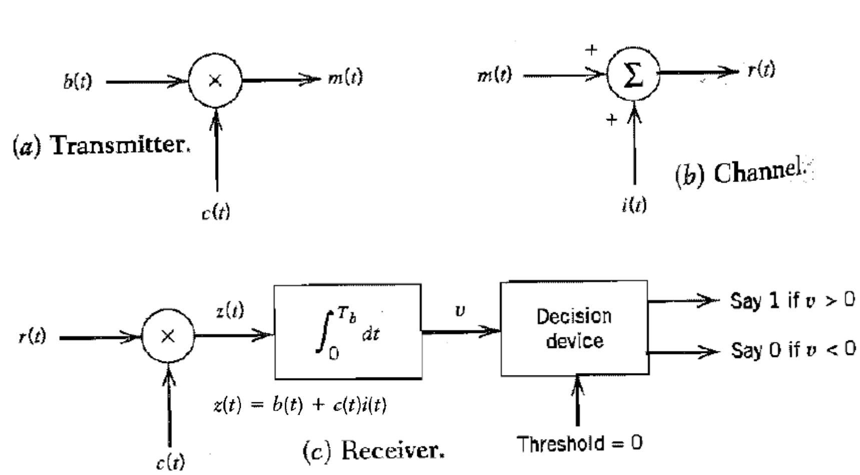


FIGURE 7.2 Maximal-length sequence generator for $m = 3$.

which repeats itself with period $2^3 - 1 = 7$.

Notation of Spread Spectrum

Idealized model of baseband spread-spectrum system.



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$$m(t) = c(t)b(t)$$

$$r(t) = m(t) + i(t) = c(t)b(t) + i(t)$$

$$z(t) = c(t)r(t) = c^2(t)b(t) + c(t)i(t)$$

$c^2(t) = 1$ for all t (-1 and $+1$)

$$z(t) = b(t) + c(t)i(t)$$

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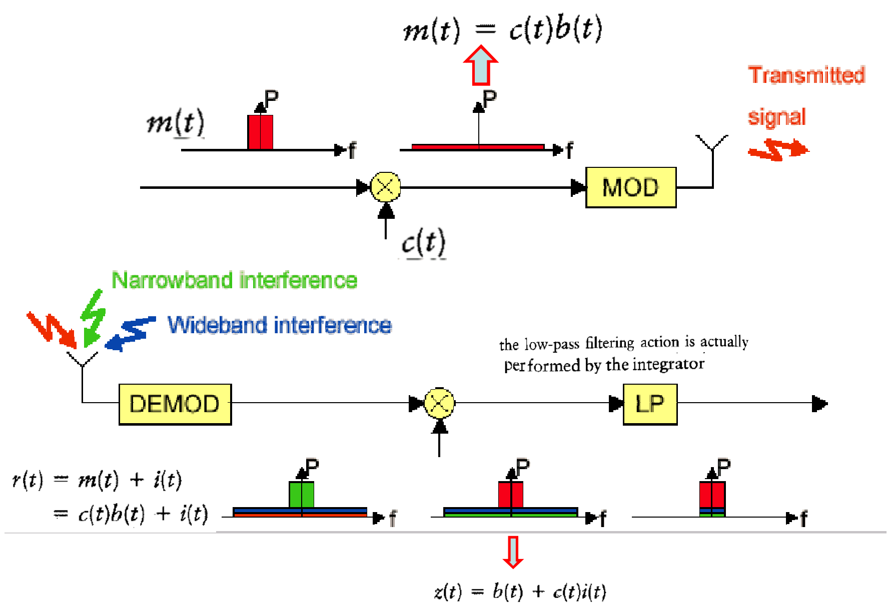

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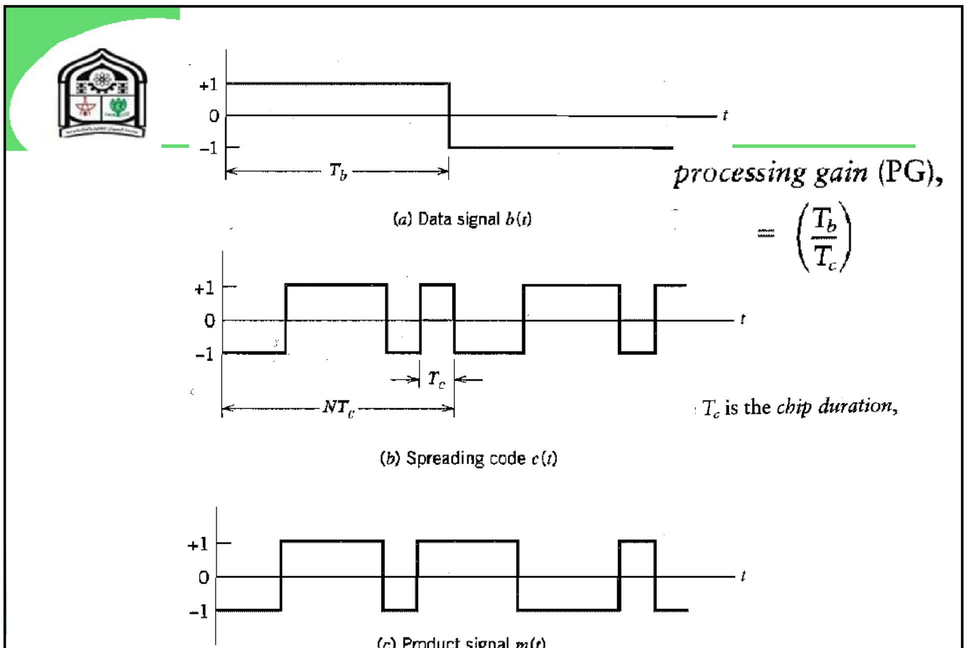

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$$\frac{N_0}{2} = \frac{JT_c}{2} \quad \xrightarrow{E_b = PT_b} \quad \frac{E_b}{N_0} = \left(\frac{T_b}{T_c}\right)\left(\frac{P}{J}\right)$$

P is the average signal power
J is the average interference power

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Anti-Jamming characteristics

$$\frac{J}{P} = \frac{\mathrm{PG}}{E_b/N_0}$$

$$(\text{Jamming margin})_{\mathrm{dB}} = (\text{Procesing gain})_{\mathrm{dB}} - 10\log_{10}\left(\frac{E_b}{N_0}\right)_{\min}$$

EXAMPLE 7.3

A spread-spectrum communication system has the following parameters:

$$\text{Information bit duration, } T_b = 4.095 \text{ ms}$$
$$\text{PN chip duration, } T_c = 1\ \mu s$$

the average probability of error is not to exceed 10^{-5}
$E_b/N_0 = 10$

$\Rightarrow$ PG = 4095

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Correspondingly, the required period of the PN sequence is $N = 4095$, and the shift-register length is $m = 12$.

$$\begin{aligned}(\text{Jamming margin})_{\text{dB}} &= 10\log_{10} 4095 - 10\log_{10}(10)\\ &= 36.1 - 10\\ &= 26.1 \text{ dB}\end{aligned}$$

That is, information bits at the receiver output can be detected reliably even when the noise or interference at the receiver input is up to 409.5 times the received signal power. Clearly, this is a powerful advantage against interference (jamming), which is realized through the clever use of spread-spectrum modulation.

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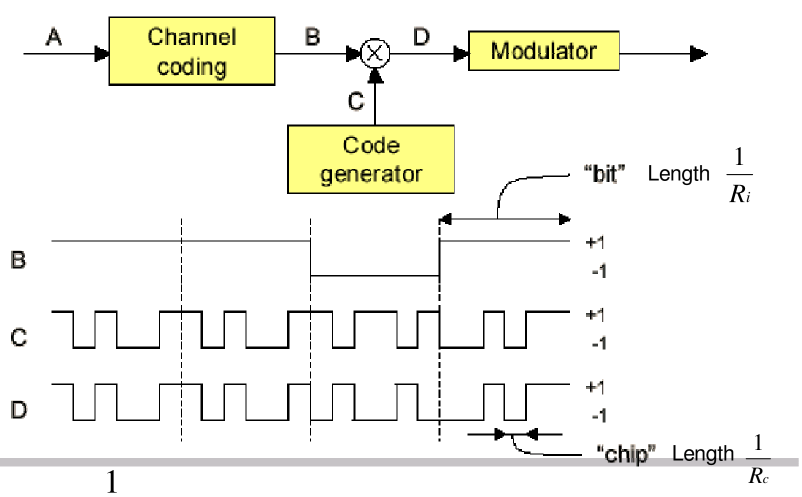
DS-CDMA Spreading



$$\frac{\frac{1}{R_i}}{\frac{1}{R_c}} = \frac{R_c}{R_i}$$

SPREADING FACTOR

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Example TX

Data	2 1								3 -1							
x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Spreading Code	1	-1	1	-1	-1	1	-1	1	1	-1	1	-1	-1	1	-1	1
=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=
CDMA																

Example TX

Data	1								-1							
x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Spreading Code	1	-1	1	-1	-1	1	-1	1	1	-1	1	-1	-1	1	-1	1
=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=
CDMA	1															

Example TX

Data	1								-1							
x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Spreading Code	1	-1	1	-1	-1	1	-1	1	1	-1	1	-1	-1	1	-1	1
=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=
CDMA	1	-1														

Example TX

Data	1								-1							
x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Spreading Code	1	-1	1	-1	-1	1	-1	1	1	-1	1	-1	-1	1	-1	1
=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=
CDMA	1	-1	1	-1	-1	1	-1	1								

Example TX

Data	1								-1							
x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Spreading Code	1	-1	1	-1	-1	1	-1	1	1	-1	1	-1	-1	1	-1	1
=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=
CDMA	1	-1	1	-1	-1	1	-1	1	-1							

Example TX

Data	1								-1							
x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Spreading Code	1	-1	1	-1	-1	1	-1	1	1	-1	1	-1	-1	1	-1	1
=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=
CDMA	1	-1	1	-1	-1	1	-1	1	-1	1						

Example TX

Data	1								-1							
x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Spreading Code	1	-1	1	-1	-1	1	-1	1	1	-1	1	-1	-1	1	-1	1
=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=
7 CDMA	1	-1	1	-1	-1	1	-1	1	-1	1	-1	1	1	-1	1	-1

(Step 7)

Data
x Spreading Code
= CDMA

1	1	-1	-1
x	x	x	x
1	-1	1	-1
=	=	=	=
1	-1	-1	1

Step 8: A + B + Noise = Band

CDMA A	1	-1	1	-1	-1	1	-1	1	-1	1	-1	1	1	-1	1	-1
+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
CMDA B	1	-1	-1	1	-1	1	1	-1	-1	1	1	-1	1	-1	-1	1
+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
NOISE	3	2	3	2	5	5	3	2	5	4	5	4	2	4	5	5
=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=
BAND																

Step 8: A + B + Noise = Band

CDMA A	1	-1	1	-1	-1	1	-1	1	-1	1	-1	1	1	-1	1	-1
+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
CMDA B	1	-1	-1	1	-1	1	1	-1	-1	1	1	-1	1	-1	-1	1
+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+
NOISE	3	2	3	2	5	5	3	2	5	4	5	4	2	4	5	5
=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=
BAND	5	0	3	2	3	7	3	2	3	6	5	4	4	2	5	5

Example RX

9 BAND	5	0	3	2	3	7	3	2	3	6	5	4	4	2	5	5
x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Spreading Code	1	-1	1	-1	-1	1	-1	1	1	-1	1	-1	-1	1	-1	1
=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=
10 Demod	5															
Add these	+								+							
Total																
1 or -1?																

Example RX

BAND	5	0	3	2	3	7	3	2	3	6	5	4	4	2	5	5
x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Spreading Code	1	-1	1	-1	-1	1	-1	1	1	-1	1	-1	-1	1	-1	1
=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=
10 Demod	5	0	3	-2	-3	7	-3	2	3	-6	5	-4	-4	3	-5	5
Add these	+								+							
11 Total																
1 or -1?																

Example RX

BAND	5	0	3	2	3	7	3	2	3	6	5	4	4	2	5	5
x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Spreading Code	1	-1	1	-1	-1	1	-1	1	1	-1	1	-1	-1	1	-1	1
=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=
Demod	5	0	3	-2	-3	7	-3	2	3	-6	5	-4	-4	3	-5	5
Add these	+								+							
Total	9								-3							
1 or -1?																

11

Example RX

BAND	5	0	3	2	3	7	3	2	3	6	5	4	4	2	5	5
x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Spreading Code	1	-1	1	-1	-1	1	-1	1	1	-1	1	-1	-1	1	-1	1
=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=	=
Demod	5	0	3	-2	-3	7	-3	2	3	-6	5	-4	-4	3	-5	5
Add these	+								+							
Total	9								-3							
1 or -1?	1								-1							

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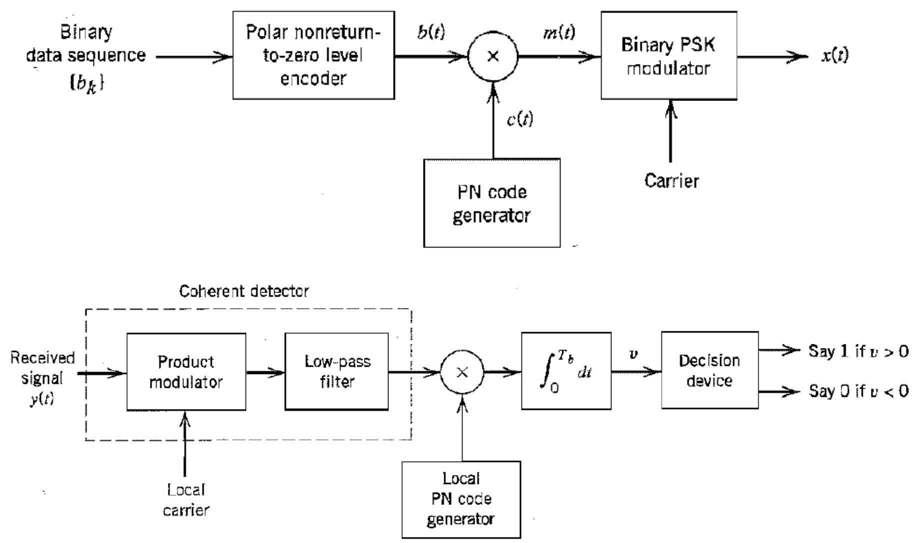
Direct-sequence spread coherent phase-shift keying.



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DS-SS challenges

- Very small chip is difficult in practical

- Synchronization
  - PN code in transmitter and receiver should be synchronized.

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Synchronization

- Synchronization is consists of two parts
  - Acquisition
    - Coarse sync
    - Fast
    - Sync to a fraction of chip
  - Tracking
    - Fine sync
    - Accomplished using phase-locked technique

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Frequency-hop Spread Spectrum

alternative method is to force the jammer to cover a wider spectrum by *randomly hopping* the data-modulated carrier from one frequency to the next.

transmitted signal is spread *sequentially* rather than instantaneously;

A common modulation format for FH systems is that of *M-ary frequency-shift keying* (MFSK).

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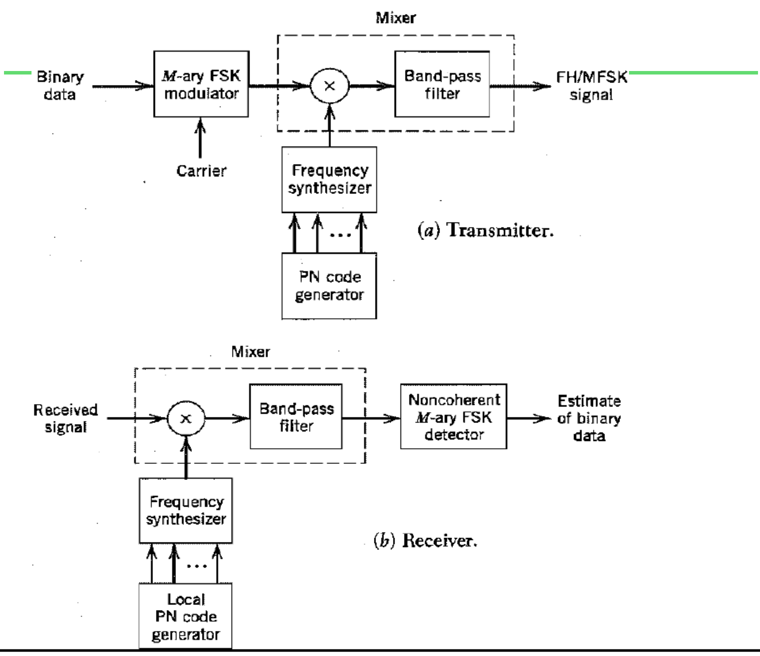
Frequency-hop spread M-ary frequency-shift keying.



(a) Transmitter.

(b) Receiver.

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Characteristics of FH

1. *Slow-frequency hopping*, in which the *symbol rate* R_s of the MFSK signal is an integer multiple of the *hop rate* R_h. That is, several symbols are transmitted on each frequency hop.

$$R_c = R_s = \frac{R_b}{K} \geq R_h \qquad \text{the hop rate } R_h$$

2. *Fast-frequency hopping*, in which the hop rate R_h is an integer multiple of the MFSK symbol rate R_s. That is, the carrier frequency will change or hop several times during the transmission of one symbol.

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Slow Frequency Hopping

- GSM uses Slow Frequency Hopping (SFH).
- In GSM, the operating frequency is changed every TDMA frame with 217 hop per second.

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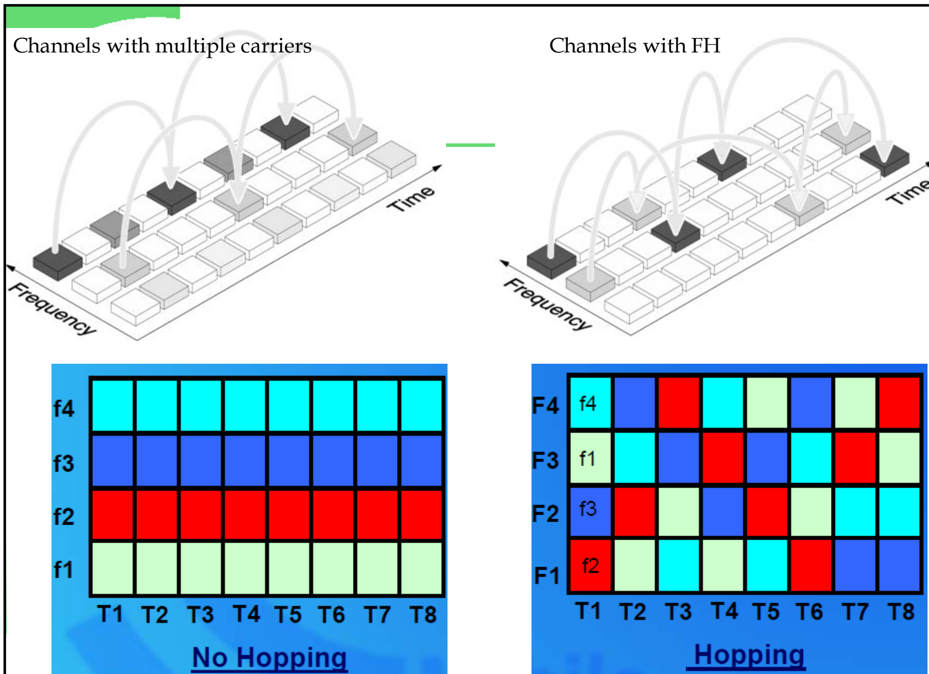

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